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# The forward photon production and the gluonic content of the real and virtual photon at the HERA collider

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## Abstract

The discussion on the production of prompt photons with  $p_T$  of a few GeV in the tagged process  $ep \rightarrow e\gamma X$  with small  $Q^2$  (DIC process) at the HERA collider is presented. Photons produced in the forward (proton) direction are mainly originating from subprocesses involving interactions of the gluonic content of the exchanged photon. The large enhancement over the Born term (direct photon) is found up to a factor of 35 for a real photon and up to 5 for a virtual photon with a squared virtuality  $1 \text{ GeV}^2$ . It gives a possibility of extracting a gluonic density of the real and of the virtual photon. The BFKL approach to the description of the forward particle production is shortly discussed.

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# The forward photon production and the gluonic content of the real and virtual photon at the HERA collider\*

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The discussion on the production of prompt photons with  $p_T$  of a few GeV in the tagged process  $ep \rightarrow e\gamma X$  with small  $Q^2$  (DIC process) at the HERA collider is presented. Photons produced in the forward (proton) direction are mainly originating from subprocesses involving interactions of the gluonic content of the exchanged photon. The large enhancement over the Born term (direct photon) is found up to a factor of 35 for a real photon and up to 5 for a virtual photon with a squared virtuality 1 GeV<sup>2</sup>. It gives a possibility of extracting a gluonic density of the real and of the virtual photon. The BFKL approach to the description of the forward particle production is shortly discussed.

## 1. Introduction

### 1.1. The DIC process at HERA

The production of the prompt photon with a large transverse momentum in  $ep$  collision under antitagging or untagging conditions is dominated by events with almost real photons mediating the  $ep$  interaction,  $Q^2 \approx 0$ . So in practice the photoproduction of the prompt photon, the Deep Inelastic Compton (DIC) scattering, is considered. The observed final  $\gamma$  arise directly from a hard subprocess or from a fragmentation process, where  $q$  or  $g$  'decays' into  $\gamma$ .

This DIC process with two real photons first offered an opportunity to test the Parton Model idea [1] and later the Quantum Chromodynamics with LO and NLO accuracy [2–10]. Next, the isolation restriction of the final photon needed in experimental analyses [11–13] was imposed in the

NLO calculations [14]. Recently the NLO approaches with the isolation of the final photon and other experimental cuts [15–18] were applied successfully to describe the data measured at the HERA collider [12,13].

The sensitivity of the DIC process to test the parton densities in the photon (and in the proton) was realized and studied for the HERA collider already ten years ago [5–9]. The conclusion was reached that the processes initiated by the gluons from the photon dominate in events where the final photon is produced in the forward direction, i.e. in the direction of the initial proton. This is a specific kind of an inverse Compton process characterized by very energetic final photons [5–8]. The tagging condition, limiting the virtuality and the energy of the exchanged photon, allows to separate the individual contributions, especially these with the gluonic content of the photon [7,8] (see also [10]).

The DIC process with so called resolved photon (i.e. interacting via its partons) takes place also for the virtual photon. This occurs when the (positive) virtuality of the exchanged photon, denoted below by  $P^2$ <sup>(4)</sup>, differs from zero and yet is

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<sup>4</sup>It is convenient to denote the virtuality of the photon-target by  $P^2$ , while use  $Q^2$  if the photon plays a role of a probe.

still small compared to the hard scale of the partonic subprocesses given by the transverse momentum of the final photon,  $P^2 \ll p_T^2$ . Then an opportunity arises to test partonic (gluonic) structure of the virtual photon in a similar manner as for a (almost) real photon mentioned above [19,20].

The recent HERA data for the jet production processes allowed so far to extract a combination of parton densities - the so called effective parton distribution in the virtual photon [21]. We argue that the photon production (DIC process) may play an complementary role in testing the structure of virtual photon [22]. Although it appears at lower rate the production of photon has an advantage being dominated in the forward direction by only one, a gluon initiated subprocess. Therefore the DIC process may allow to separate and extract the fundamental, although less known experimentally, gluonic density in the virtual photon.

### 1.2. Forward particle production as a test of QCD dynamics at small $x_{Bj}$

Recently a forward jet and particle production, among them  $\pi^0$  and  $\pi^\pm$ , has been studied at HERA [23,24] in order to test QCD dynamics at small  $x_{Bj}$ . The question is what is the proper type of partonic evolution (BFKL, DGLAP or CCFM?) in the chain between the virtual photon and the proton for the DIS events at small  $x_{Bj}$ . In such analysis the positive virtuality of the exchanged photon,  $P^2$ , plays a role of the standard DIS  $Q^2$  variable. It is well known that the BFKL evolution corresponds to not strongly ordered in  $p_T$  parton emission and leads to larger transverse momenta of final gluons than the DGLAP evolution based on the collinear gluon emissions. Therefore in search for a signal of the BFKL evolution the transverse momentum of the final forward particle is usually chosen to be large and of order of  $P^2$ .

The resolved virtual photon contribution leads to BFKL-type final state configurations, as it was pointed out in [25]. Although such contributions is suppressed for  $p_T^2 \sim P^2$  (lack of corresponding large logarithms present in the standard DGLAP description of the virtual photon structure, where

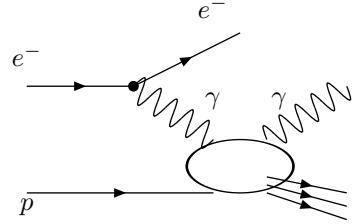


Figure 1. The DIC process

$p_T^2 \gg P^2$ ), one should be aware that the forward particle production may arise from a mechanism not obviously included in the BFKL evolution equation [25,26].

The newest ZEUS data [24] for the forward jet production studied in the range  $10^{-2} < p_T^2/P^2 < 10^2$  show that only model which includes resolved photon components, with a hard scale  $\tilde{Q}^2 = P^2 + p_T^2$ , describe the data in the whole kinematic range. On the other hand a new analysis [27] shows that CCFM approach can describe properly the forward jet production at HERA as well, while the H1 data for forward  $\pi^0$  [23] seems to support a modified (i.e. with a limited  $p_T$  phase space) BFKL evolution equation [28].

In this presentation we focus on the production of very energetic forward photons with  $p_T \sim 5$  GeV in the DIC process for  $P^2 \ll p_T^2$  and we show that it may offer an opportunity to probe the gluonic content of the virtual photon at HERA.<sup>5</sup>

### 2. Probing parton densities in $\gamma^*$ in the DIC process at HERA

We continue our study [20] of the inclusive DIC process

$$ep \rightarrow e\gamma X \quad (1)$$

for a relatively small momentum transfer between the initial and the final electron, where the ex-

<sup>5</sup>The analysis of the forward  $\gamma$  production at HERA as a signature of the BFKL evolution can be found in [29].

change of a virtual photon dominates over the  $Z$  boson exchange. We will limit ourselves to events with the tagged electrons, so the energy and (positive) virtuality of the exchanged photon  $-p^2 = P^2$  are known.

The first attempt to describe the DIC process at HERA using the structure of the virtual photon can be found in [19], where the Equivalent Photon Approximation (EPA) approach was compared with the calculation involving direct and resolved virtual photons. Next we have examined the usefulness of DIC process to study at the HERA collider the structure of a virtual photon, in particular its gluonic content [20]. Here we extend this analysis by comparing compare different contributions to the DIC cross section in the  $ep$  LAB reference frame and by studying a wider virtuality range:  $P^2$  from 0 to 2.5 GeV $^2$ .

## 2.1. Born term and subprocesses involving resolved $\gamma^*$

We consider the virtual photon - proton interaction leading to the production of the large  $p_T$  photon. It corresponds to the following direct subprocess at the lowest order (Born level):

$$\gamma^* q_p \rightarrow \gamma q, \quad (2)$$

with the initial and final photon interacting directly with a quark from the proton. The Born process dominates at *very large*  $p_T \sim \sqrt{S_{ep}}/2$  ( $x_T = \frac{2p_T}{\sqrt{S_{ep}}} \sim 1$ ), while in the *moderate*  $p_T$  region which we will consider here, i.e. for  $\Lambda_{QCD}^2 \ll P^2 \ll p_T^2 \ll S_{ep}/4$ , resolved virtual photon processes become important. There are three types of LO subprocesses involving the partonic constituents of the initial and/or final photons in DIC process:

- with single resolved initial photon

$$g_{\gamma^*} q_p \rightarrow \gamma q, \quad (3)$$

$$q_{\gamma^*} g_p \rightarrow \gamma q, \quad (4)$$

$$q_{\gamma^*} \bar{q}_p \rightarrow \gamma g \quad (5)$$

$$\bar{q}_{\gamma^*} q_p \rightarrow \gamma g \quad (6)$$

- with single resolved final photon (fragmentation into the photon)

$$\gamma^* g_p \rightarrow q \bar{q} \quad (7)$$

$$\gamma^* q_p \rightarrow g q \quad (8)$$

- with double resolved photons

$$g_{\gamma^*} g_p \rightarrow gg \quad (9)$$

$$q_{\gamma^*} g_p \rightarrow qg, \text{ etc.} \quad (10)$$

In this talk we limit ourselves to the processes involving single resolved initial photon. We expect to see the effect due to the gluonic content in the virtual photon by looking into a final photon produced in the forward direction. The remaining subprocesses are known [20] to give smaller contributions in this region.

## 2.2. Calculation of the cross section

The differential cross section for deep inelastic electron-proton scattering with a photon in the final state, eq. (1), can be written in the following form:

$$E_e E_\gamma \frac{d\sigma_{ep \rightarrow e\gamma X}}{d^3 p_e d^3 p_\gamma} = \Gamma_T \left( E_\gamma \frac{d\sigma^{\gamma^* p \rightarrow \gamma X}}{d^3 p_\gamma} \right) |_T + \Gamma_L \left( E_\gamma \frac{d\sigma^{\gamma^* p \rightarrow \gamma X}}{d^3 p_\gamma} \right) |_L, \quad (11)$$

where  $E_e (E_\gamma)$  and  $p_e (p_\gamma)$  are the energy and the momentum of the final state electron (photon). Coefficients  $\Gamma_T$  and  $\Gamma_L$  (functions of the energy and momentum of the electron in the initial and final state) can be interpreted as the probability of emitting by the initial electron a virtual photon polarized transversely and longitudinally.

Since the cross section for the reaction  $ep \rightarrow e\gamma X$  is dominated by the exchange of the photon with small virtuality, one can neglect a contribution due to the longitudinal polarization. (See also [31], where the role of the longitudinal photons is discussed for the Born term, and where it was found that the longitudinal polarizations can be neglected even for  $P^2$  larger than studied

here). Assuming that the exchanged photon has only the transverse polarization we obtain:

$$E_e E_\gamma \frac{d\sigma^{ep \rightarrow e\gamma X}}{d^3 p_e d^3 p_\gamma} = \Gamma_T E_\gamma \frac{d\sigma^{\gamma^* p \rightarrow \gamma X}}{d^3 p_\gamma} |_T. \quad (12)$$

where we include contributions from subprocesses (2)-(6). In the calculations of the cross section for the  $\gamma^* p$  collision functions describing parton densities appear. They depend on a hard scale  $\tilde{Q}^2 \sim p_T^2$ , a parton virtuality  $P^2$  and  $x_\gamma$  - the part of the photon momentum taken by the parton.

It is worth to emphasize that while calculating the cross section for individual subprocesses we take into consideration the virtuality ( $P^2$ ) of the photon emitted by the electron as it follows from the kinematics of the process.

Note that the minimum value of the  $x_\gamma$  is reached when the photon is produced in the forward (proton) direction. This fact influences the shape of the cross section as a function of rapidity what is discussed below.

### 2.3. Results

The resolved initial photon contributions to the DIC process are calculated and compare to the Born (direct) term for the HERA collider. The squared energy of the HERA accelerator ( $S_{ep}$ ) is taken as 98400 GeV<sup>2</sup> and the cross section is calculated for the transverse momentum of the final photon equal to 5 GeV and for the fixed energy of the exchanged photon:  $E_{\gamma^*} = y E_e$ , with  $y = 0.5$ .

In our calculations the GRS (LO) parton parametrizations for the parton distributions in the virtual photon [30] and the GRV (LO) set of the quark and the gluon densities for the proton [32] were used. The number of flavours is assumed  $N_f = 3$  - the maximum number of active massless quarks in the GRS parametrization. We take the QCD parameter  $\Lambda_{QCD} = 0.2$  GeV and the hard scale equal to the transverse momentum of the final photon  $\tilde{Q} = p_T$ .

The following cross section was studied:

$$E_\gamma \frac{d\sigma^{ep \rightarrow e\gamma X}}{d^3 p_\gamma dP^2 dy} = \frac{1}{2\pi} \frac{E_\gamma}{p_T^2} \frac{d\sigma^{ep \rightarrow e\gamma X}}{dE_\gamma dY dP^2 dy}, \quad (13)$$

where  $Y$  denotes the  $ep$  LAB rapidity of the produced photon (its positive value corresponds to the proton direction).

The cross section dependence on rapidity was tested using various values of  $P^2$  between  $\sim 0$  and 2.5 GeV<sup>2</sup>. The results are presented in Figures 2 and 3. Fig. 2 shows the ratio of the cross section (13) for the subprocess  $g_{\gamma^*} q_p \rightarrow \gamma q$  to the Born contribution as a function of the rapidity  $Y$ . For comparison also the ratios of  $q_{\gamma^*} g_p \rightarrow \gamma q$  and  $q\bar{q} \rightarrow \gamma g$  subprocesses to the Born term are plotted.

The virtuality  $P^2$  for the reaction  $g_{\gamma^*} q_p \rightarrow \gamma q$  varies from  $10^{-7}$  GeV<sup>2</sup> <sup>(6)</sup> to 1 GeV<sup>2</sup>, while for the other two subprocesses involving the quark or antiquark content of  $\gamma^*$  only the case of  $P^2=0.1$  GeV<sup>2</sup> is presented (results for higher  $P^2$  are even smaller).

The clear dominance of the process  $g_{\gamma^*} q_p \rightarrow \gamma q$  over the Born contribution and over the other two types of subprocesses with a single resolved virtual photon is seen in the forward direction. Even for  $P^2=1$  GeV<sup>2</sup> the corresponding cross section ratio reaches maximum value of about 6 at  $Y_0=4.8$ . The position of the peak is almost independent of  $P^2$  and it is related to the smallest value of  $x_\gamma$  tested in the subprocess ( $\min x_\gamma \sim x_T^2$  and  $Y_0^{CM} \sim -\ln x_T$ , see [5]).

The same cross section ratio, now only for the dominating subprocess  $g_{\gamma^*} q_p \rightarrow \gamma q$ , as a function of the virtuality  $P^2$  for three different values of positive  $Y$  is presented in Fig. 3. The large enhancement of the contribution due to the gluonic content of the virtual photon over the Born term is seen in the proton direction for the considered virtuality range.

This dominance of the  $g_{\gamma^*} q_p$  process is so large that the change of parameters (among them the number of active flavours) and/or parton parametrizations will not change the main conclusion. The conclusion will remain unchanged also when imposing an experimental isolation restrictions for the final photon, because the isolation does not change the cross section for the dominant subprocesses (2-6) considered herein[16–18].

Note also that the interference with the Bethe-Heitler process, discussed in [33], is small for  $p_T=5$  GeV and in the region of the rapidity where

<sup>6</sup>Due to smooth behaviour of the GRS parametrization in the limit  $P^2 \rightarrow 0$  we were able to perform the calculation also below  $\Lambda_{QCD}^2$ .

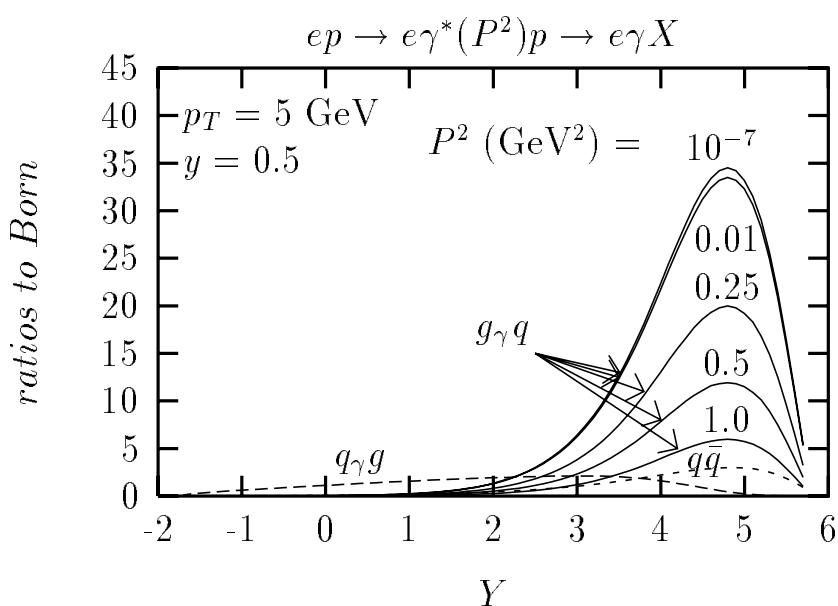


Figure 2. Ratios of the cross sections (see eq. 13) for the reaction  $ep \rightarrow e\gamma^*(P^2)p \rightarrow e\gamma X$ , with  $y=0.5$  and  $p_T = 5$  GeV. The ratios of the contributions due to  $g_{\gamma^*}q_p \rightarrow \gamma q$  (solid lines),  $q_{\gamma^*}g_p \rightarrow \gamma q$  (long-dashed line) and  $\bar{q}_{\gamma^*}q_p \rightarrow \gamma g$  (short-dashed line) to the Born cross section are presented for various values of the virtuality  $P^2$  as a function of the rapidity  $Y$ . For  $g_{\gamma^*}q_p \rightarrow \gamma q$  the results correspond to  $P^2 = 10^{-7}, 0.01, 0.25, 0.5$  and  $1$   $\text{GeV}^2$ . For  $q_{\gamma^*}g_p \rightarrow \gamma q$  and  $\bar{q}_{\gamma^*}q_p \rightarrow \gamma g$  we take  $P^2 = 0.1$   $\text{GeV}^2$ .

the gluonic content of the virtual photon plays a dominant role [34].

### 3. Conclusions

We have considered the LO cross section for tagged DIC events corresponding to the  $\gamma^*p$  scattering including the direct and resolved virtual photon subprocesses at the HERA collider. The GRS( $\gamma^*$ ) and GRV( $p$ ) parton parametrizations were used for  $N_f=3$ . The final photon rapidity dependence was studied for typical values of the variables,  $y=0.5$  and  $p_T=5$  GeV, and virtualities of the exchanged photon from 0 to  $2.5$   $\text{GeV}^2$ . The ratios of single resolved photon contributions to the Born contribution were studied as a function of the rapidity and as a function of  $P^2$ .

The contribution due to gluonic content of the virtual photon was found to dominate over other subprocesses in the direction of the initial proton. This can have important consequences for the possibility of measuring the gluon distribution in the virtual photon at HERA. The DIC process may be treated as complementary to the

jet production which have allowed recently to extract the effective parton density in the virtual photon at HERA.

Finally, it is worth to mention that the forward photon production in DIC process leads to the configurations typical for the study of the BFKL dynamics at small  $x_{Bj}$ .

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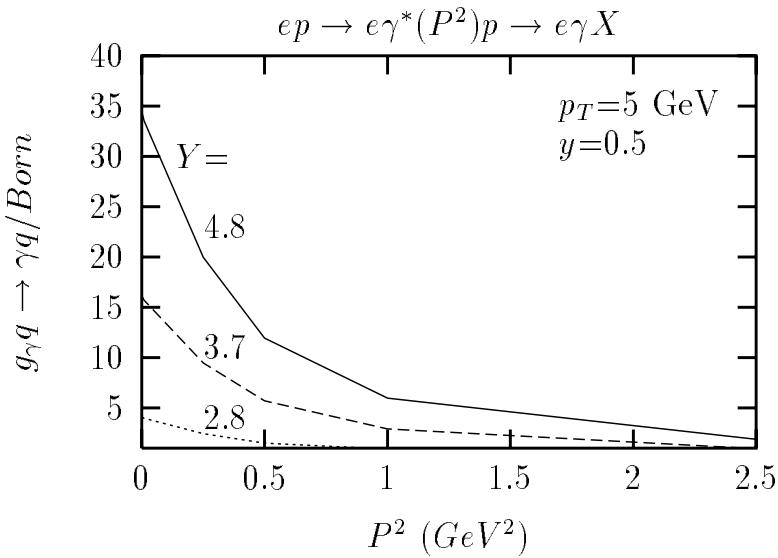


Figure 3. The ratio of the cross sections  $\frac{d\sigma^{ep \rightarrow e\gamma^*X}}{dE_\gamma dY dP^2 dy}$  for  $p_T = 5$  GeV and  $Y = 0.5$ :  $g_{\gamma^*q} \rightarrow \gamma q$  contribution divided by the Born contribution. The lines show the results as a function of the initial photon virtuality  $P^2$ . The final photon rapidity  $Y$  is equal to 2.8 (dotted line), 3.7 (dashed line) and 4.8 (solid line).

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